Neutron thermalization in Liquid Argon

A "Back of the envelope" style calculation.

Starting point(s): measured thermalization time in other materials

- Thermalization in water: subject to calculations, simulations and measurements over many decades, using "fission neutrons" (typically 2 MeV, so comparable to DD generator neutrons). The "full thermalization" claimed to be $25 - 30\,\mu$s; thermalization sufficient to see significant neutron captures $\sim 2.5\,\mu$s. Thermalization is from scattering from protons. Assume scattering cross-section is $1/v$, which is not completely accurate for protons, and for energies above epithermal, but is "close enough". From the NNDC ENDF listing for elastic scatters at $E = 0.025\,\mathrm{eV}$,$\sigma_s(v_{th}) = 30.2\,\mathrm{b}$

$$n_H = 2 \times \frac{1.0\,\mathrm{g/cm^3}}{18\,\mathrm{g/mol}} 6.02 \times 10^{23}\,/\mathrm{mol} = 6.7 \times 10^{22}\,/\mathrm{cm^3} \tag{1}$$

$$\sigma_{scat}(v) = \left(\frac{v_{th}}{v}\right) \sigma_{scat}(v_{th}) \tag{2}$$

$$\xi_H = 1 \tag{3}$$

$$N_{thermalize} = \frac{1}{\xi_H} \ln\left(\frac{E_0}{E_{th}}\right) \tag{4}$$

$$= \frac{1}{1} \ln\left(\frac{2 \times 10^6\,\mathrm{eV}}{25 \times 10^{-3}\,\mathrm{eV}}\right) = 18.2 \tag{5}$$

Mean free path between scatters:

$$L = n_H \sigma_{scat}(v) \tag{6}$$

Time between scatters:

$$T = 1/n_H \sigma_{scat}(v) v \tag{7}$$

$$= 1/n_H \sigma_{scat}(v_{th}) v_{th} \tag{8}$$

$$= \left[\left(6.7 \times 10^{22}\,/\mathrm{cm^2}\right)\left(30.2 \times 10^{-24}\,\mathrm{cm^2}\right)\left(2.2 \times 10^5\,\mathrm{cm/s}\right)\right]^{-1} \tag{9}$$

$$= 2.3\,\mu\mathrm{s} \tag{10}$$

and

$$T_{thermalize} = N_{thermalize} T \tag{11}$$

$$= 42\,\mu\mathrm{s} \tag{12}$$

For n,p elastic scattering, can get neutrons at very low energy after a single scatter, so the "some captures within $2.5\,\mu$s" is consistent. The overall thermalization seems consistent with roughly a factor of two.

- Liquid Argon; first just treat as if it is at "room temperature", and that the liquid argon consists entirely of ^{40}Ar, since the other isotopes contribute very little to the scattering, as shown by this table caculating the macroscopic cross section ($\Sigma = n\sigma$)

isotope	abundance	σ_s (2200 m/s)	n	$\Sigma_s = n\sigma_s$
^{36}Ar	0.334%	74.61 b	7.05×10^{19} /cm^3	5.26×10^{-3} /cm
^{38}Ar	0.064%	8.94 b	1.35×10^{19} /cm^3	1.21×10^{-4} /cm
^{40}Ar	99.604%	0.655 b	2.10×10^{22} /cm^3	1.38×10^{-2} /cm
all	100%	0.91 b	2.10×10^{22} /cm^3	1.92×10^{-2} /cm

$$n_{Ar} = \frac{1.4\,\mathrm{g/cm^3}}{40\,\mathrm{g/mol}} 6.02 \times 10^{23}\,\mathrm{/mol} = 2.11 \times 10^{22}\,\mathrm{/cm^3} \quad (13)$$

$$\sigma_{scat}(v) = \sigma_{scat}(v_{th}) \frac{v_{th}}{v} = (0.91\,\mathrm{b})\,\frac{v_{th}}{v} \quad (14)$$

$$\xi_{Ar} = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1} = 4.9 \times 10^{-2} \quad (15)$$

$$N_{thermalize} = \frac{1}{4.9 \times 10^{-2}} \ln \left(\frac{2 \times 10^6\,\mathrm{eV}}{2.5 \times 10^{-2}\,\mathrm{eV}} \right) = 370 \quad (16)$$

$$\begin{aligned} T &= [n\sigma_s(v)v]^{-1} && (17) \\ &= \left[n\sigma_s\,(v_{th})\,\frac{v_{th}}{v} v \right]^{-1} && (18) \\ &= \left[\Sigma_s^{tot}\,(v_{th})\,v_{th} \right]^{-1} && (19) \\ &= \left[\left(1.92 \times 10^{-2}\,\mathrm{/cm}\right) \left(2.2 \times 10^5\,\mathrm{cm/s}\right) \right]^{-1} && (20) \\ &= 240\,\mu\mathrm{s} && (21) \end{aligned}$$

and so

$$\begin{aligned} T_{thermalize} &= 370 \times (240\,\mu\mathrm{s}) && (22) \\ &= 88\,\mathrm{ms} && (23) \end{aligned}$$

It takes even more scatters to reduce the temperature from 300 K to 87 K, but even ignoring that (because it is just another 25 scatters, so less than a 10% effect) the time to thermalize in Argon is much, much longer than thermalization in water.

We can characterize the ratio between thermalization of neutrons in water and liquid argon from three major factors:

- 33 times higher scattering cross section on protons compared to Argon. (ENDF scattering cross section at 25 milli-eV).
- 20 times more collisions needed to thermalize, because of kinematics
- Number density of protons 3.2 times that of Argon.

All of which work to make thermalization in liquid argon $\sim$ 2000 times slower than in water, however one wants to characterize how close to "fully thermalized" is desired.